MARCH 1990

POTENTIAL FOR PHYSICAL INJURY, OTHER THAN HEARING DAMAGE, TO DOLPHINS FROM SEAL BOMBS USED IN THE YELLOWFIN TUNA PURSE-SEINE FISHERY: RESULTS FROM OPEN-WATER TESTS

By

Albert C. Myrick Jr.
Edward R. Cassano
Charles W. Oliver

ADMINISTRATIVE REPORT LJ-90-07

This administrative Report is issued as an informal document to ensure prompt dissemination of preliminary results, interim reports and special studies. We recommend that it not be abstracted or cited.

POTENTIAL FOR PHYSICAL INJURY, OTHER THAN HEARING DAMAGE, TO DOLPHINS FROM SEAL BOMBS USED IN THE YELLOWFIN TUNA PURSE-SEINE FISHERY: RESULTS FROM OPEN-WATER TESTS

Albert C. Myrick, Jr.,

Edward R. Cassano,

and

Charles W. Oliver

Southwest Fisheries Center

National Marine Fisheries Service, NOAA

La Jolla, California 92038

March 1990

ADMINISTRATIVE REPORT LJ-90-07

TABLE OF CONTENTS

Page

ABSTRACT 1

INTRODUCTION 1

METHODS AND MATERIALS 3

RESULTS

Relative Strengths..... 6

Determining Impulse Pressures from Fish Damage..... 10

DISCUSSION

Explosion Pressures..... 11

Injury from Impulse Pressures..... 11

Estimation of "Safe Ranges"..... 13

Are Seal-bomb Data Applicable?..... 14

CONCLUSIONS 15

ACKNOWLEDGEMENTS 16

LITERATURE CITED..... 17

LIST OF TABLES

Table		Page
1.	Results of open-water tests of seal bombs on targets (July 26, 1989).....	19
2.	Results of open-water tests of seal bombs on targets (October 10, 1989)	20
3.	Fish mortality, injury, and weight in open-water tests with single and simultaneously detonated pairs of Class-C seal bombs (October 10 1989).....	21

LIST OF FIGURES

Figure | Page

1. Floating target array used to test damage from underwater detonations of seal bombs..... 22

2. Underwater deployment of bottles, cans, and dolphin carcasses as targets to test seal bomb damage..... 23

3. Damage to air cans showing polygonal deformation. A: Can #8 on right damaged by Panamanian unit at 0.7 m (shot 19). B: Can #10 damaged by Class-C cluster at 0.6 m (shot 16)..... 24

4. A: Damage to dolphin carcass from Panamanian unit at 0.6 m. B: Examination of shoulder damage. Note fragments of shattered scapula in right foreground..... 25

5. Plots of weights of fish (g) against percent injury and mortality to get impulse pressures for seal bomb explosions in open-water tests on 10 October 1989 (after Yelverton et al. 1975)..... 26

6. Use of curves from Yelverton et al. (1975) to predict standoff ranges for mammals from underwater seal-bomb explosions for 2.0, 2.5, 3.0, and 4.0-g charge weights, where target (T) and bomb (B) depths are 1-1, 2.5-1, 1-3, and 2.5-3 m respectively (refer to boxes in upper left). Vertical bars indicate degree of injury at distances marked by arrows on right-hand margin... 27

7. Use of curves from Yelverton et al. (1975) to predict standoff ranges for mammals from underwater seal-bomb explosions for standard U.S.-made unit with 2.33 g of explosive, where target (T) and bomb (B) depths are 1-1, 2.5-1, 1-3, and 2.5-3 m respectively, calculated for charges with 100, 80, 70, and 50% TNT equivalency. Vertical bars indicate degree of injury at distances marked by arrows on right-hand margin. Dark horizontal lines show standoff distances for 80% TNT-equivalent charge..... 28

Potential for physical injury, other than hearing damage, to dolphins from seal bombs used in the yellowfin tuna purse-seine fishery: results from open-water tests

By
Albert C. Myrick, Jr., Edward R. Cassano, and Charles W. Oliver
Southwest Fisheries Center
National Marine Fisheries Service, NOAA
La Jolla, California 92038

ABSTRACT

We exploded pre-positioned seal bombs on stationary underwater targets including air-filled cans, water-filled cans, dolphin carcasses, and cages of live fish to determine 1) whether the explosives were strong enough to cause direct physical injury to dolphins, and 2) if so, what were safe standoff ranges. From our results, we would expect that a Class-C seal bomb will cause injury when detonated within 0.5 to 0.6 m of a dolphin. We estimated a safe standoff distance to be 4.0 m, or slightly more depending on explosive and swimmer depth. Throughout this study, we have struggled with the problem of using criteria from studies of explosions on submerged land mammals to predict effects of seal bombs on free-swimming dolphins.

INTRODUCTION

Since about 1960, when purse seining had largely replaced "pole and line fishing" in the yellowfin tuna fishery in the eastern tropical Pacific, dolphins have been chased and set upon to ensure the capture of yellowfin tuna that follow them (Perrin 1969). To control and concentrate dolphin schools up to the time the purse seine is deployed, the fishermen herd the animals using up to six speedboats, helicopters (on some boats), and small, hand-thrown explosives, called "pest-" or "seal-control devices," or more commonly, "seal-bombs" (Myrick et al. 1990).

Interviews with veteran National Marine Fisheries Service (NMFS) observers who accompanied fishermen on seiner fishing trips in the earlier days of the fishery, indicate that seal-bombs have been used in sets on school fish (i.e., not involving dolphins) since at least the early 1970's. (McNeely [1961] has reported use of several types of seal bombs, then called "cherry bombs," on school fish as early as the introduction of tuna purse seining itself.) Since at least 1980, seal bombs reportedly have been used by many seiners in sets on dolphins, i.e., in so-called "porpoise fishing" (Cassano et al. 1990).

Although several varieties and configurations of seal bombs have been used in recent years, most are about the size and power of an M-80 firecracker (Myrick et al. 1990; R. Robinson, California Seal Control Corp., pers. comm. 1989; Conkling 1985). They are water-resistant, sand-weighted, cylindrical units with an 8- to 15-second powder fuse that allows them to sink one to four meters below the water surface before they detonate. Depth of detonation is largely dependent upon the delay between ignition of the fuse and the bomb's entry into the water. The underwater explosion has a blast, sound, and flash component (Myrick et al. 1990). To our knowledge no measurements of the underwater explosion of seal bombs have been made except for sound pressure levels of unvented explosions (Aubrey and Thomas 1987) and of surface-vented explosions (Holliday 1972).

The Marine Mammal Protection Act of 1972 (MMPA), as amended by PL 100-711 (November 23, 1988), now restricts the use of seal bombs to Class-C-category devices, i.e., containing 40 grains (2.59 g) or less of explosive material, in commercial yellowfin tuna fishing on dolphins. Despite this current prohibition, recent reports identifying the type of seal bomb by color indicate that several types of apparently non-Class-C units are still in use by some boats in purse-seine sets on dolphins. Other reports have revealed that Class-C units are being bound together and thrown and detonated as a cluster (Cassano et al. 1990). This clustered configuration is likely to be considered illegal under the MMPA because the total weight of such a charge is greater than 2.59 g.

In addition to the restrictions to Class-C units, the MMPA as amended instructs the Secretary of Commerce "to prescribe regulations, effective April 1, 1990, to prohibit or restrict the use of Class-C explosive pest control devices in the course of commercial yellowfin tuna fishing unless [he] determines ... that the use of such devices does not result in physical impairment or increased mortality of marine mammals."

In early 1989, investigations were initiated by the Southwest Fisheries Center (NMFS) to examine major parts of this problem.

1. Study was begun of the possibility of dolphin hearing impairment from the impulse sound of seal-bomb explosions by analyzing inner-ear tissues taken from dolphins killed in the purse-seine fishery (study continuing).

2. Searches were conducted of observer logs documenting purse-seine sets on dolphins to determine the potential exposure of dolphins to seal bombs and some of the consequences of such exposure, such as differential mortality with and without use of explosives (Cassano et al. 1990).

3. Seal bombs used in the fishery were studied to determine potential hazards to dolphins, past and present (Myrick et al. 1990)

4. Literature on effects of audiogenic stress on the biology and sociology of mammals was reviewed and synthesized with focus on how this may relate to stress responses by dolphins to repeated explosions of seal bombs in purse-seine sets (Majors and Myrick 1990).

5. The potential for direct physical injury, other than to hearing, to dolphins in the fishery due to the blast and shock-wave pressure of seal-bomb explosions underwater was studied.

We report here details of the study evaluating possible direct injury to purse-seined dolphins by seal bombs based on results and implications of open-water experiments in which seal bombs were detonated on targets.

METHODS AND MATERIALS

To address the specific question: "Do seal bombs used in purse-seine sets cause direct physical injury to dolphins?," the most parsimonious approach would have been to observe live dolphins exposed to underwater seal-bomb explosions in the fishing situation and to examine killed or sacrificed focal animals for blast and pressure shock-wave injury. Partly because of anticipated delays with the logistics of such a study (including issuance of a permit authorizing this research), we focussed instead on three related questions that, if answered, could help to resolve the specific question without the need of direct experimentation on dolphins:

1. What is the energy of blast and shock-wave pressure generated by underwater explosions of various kinds of seal bombs in use?

2. Can the energy from such explosions cause direct physical injury to submerged terrestrial mammals (and if so, what are safe distances)?

3. How similar in susceptibility to such injury are dolphins to other mammals?

We conducted two series of open-water experiments, one on 26 July 1989, the other on 10 October 1989. In these tests, several types and configurations of seal bombs used in the fishery were remotely detonated at predetermined depths on submerged arrays of targets positioned at known depths and distances.

A semi-rigid rectangular framework of pvc pipe and steel cable, 3.0 x 1.5 m, was used to suspend three weighted vertical cables for positioning targets and to hold a weighted cable for positioning seal bombs. Three parallel horizontal cables, spaced 0.5 m apart, were attached lengthwise inside the frame. This arrangement permitted distances to be changed between bomb cable and target cables by sliding the target-array cables towards or away from the bomb cable. Spherical, pneumatic buoys, 0.78 m in diameter, were used for flotation (Fig. 1).

Each array cable was designed to hold four targets, with each target set at one of four depths: 0, 1.0, 2.5, and 5.0 m. A different target order was used on each cable. This design enabled us at will to expose up to 12 targets at a time, including duplicate targets at different depths, to a single blast without producing shadows that would protect targets from the direct pressure wave.

Bombs were rigged for electronic detonation by replacing the powder fuse with a toy rocket igniter, soldering the two ends of the igniter to short lengths of 18-gauge electrical wire, and sealing the end of the bomb cylinder with silicon sealer. A 12-volt motorcycle battery on one of the boats was used as the power supply for remote detonation of bombs at 0, 1.0, and 3.0-m depths in the water. Alligator clips on each end of a pair of short wires connected battery terminals to a guillotine switch. Two 10-m-long wires leading from the switch were used to accommodate depths of bombs mounted on the vertical cable. Bomb wires were connected to the lead wires by twisting them together. Duct tape was used to insulate the connections. When ready, a unit was mounted in a designated position on the bomb cable and the cable was lowered into place. When the site was clear, the alligator clips were attached to the battery terminals, and the switch was closed. After each detonation, and before swimmers entered the water to inspect and replace targets and reset gauges, the clips were removed from the terminals and the switch was opened.

The test site was located about two miles west of the pier at Scripps Institute of Oceanography, La Jolla, CA. At this distance from shore, the water is more than 100-m deep. Shots were conducted in fairly calm water of Beaufort 2 or less, with 2-3 foot swells.

We used five types of seal bombs in our tests. Two, made by the same U.S. manufacturer, representing separate generations of Class-C units, contained a potassium perchlorate ($KClO_4$) mixture explosive. One of these types, produced in 1984, bore a green label on a yellow body. The other unit, produced more recently, had an all-yellow body. The green-labeled unit contained less explosive

(mean=1.9 g, range 1.7-2.2 g, n=5) than the all-yellow one (mean=2.44 g, range 2.1-2.5 g, n=5). We tested the U.S.-made units singly, as simultaneously detonated pairs with each unit of the pair mounted at a different depth, and in clusters of 2 and 3 units each. The other three units used were foreign-made and contained various potassium chlorate ($KClO_3$) explosive mixtures (a more dangerous explosive than potassium perchlorate and illegal in Class-C seal bombs). A plain-cardboard unit from Panama contained an average of 5.76 g, but varied by as much as 1.4 g of explosive (n=3). A red-wrapped unit from Mexico contained 4.02 g (n=1) of explosive, and the charge-weight of an orange unit from Costa Rica averaged 3.82 g (range 3.0-4.1 g, n=12) (Myrick et al. 1990).

Targets for the tests on 26 July consisted of whole, freshly-thawed dolphin carcasses, numerous 16-oz aluminum beverage cans (mounted upside down on a cable they contained air [referred to hereinafter as "air cans"], mounted rightside up they contained water [referred to as "water cans"]), and sealed, plastic 2-liter bottles containing air-filled balloons surrounded by gelatin. The latter targets were intended to simulate lungs (Fig. 2). For the shots on 10 October, targets included maximum-depth diving ("strain-") gauges, heat-mount detectors of different rupture strengths (ordinarily used by cattle ranchers to detect mounting of a cow by a bull), fish cages, each usually with 5 live, swimbladdered fish (mostly Pacific mackeral), and air cans and water cans. Piezoelectric and piezoresistor gauges customarily used for recording instantaneous pressures from large underwater explosions were considered not useful for measuring the explosive force of seal bombs (J. Gaspin, Nav. Surf. Weap. Cent., pers. comm. 1989).

Carcasses were visually inspected externally and sketched before being taken out to the test area. At the end of the test day, carcasses were returned to the La Jolla Laboratory and refrozen for later external comparison with the pre-test sketches and for internal examination for damage.

All mounted targets were inspected by swimmers immediately before and after each shot. Descriptions of damaged targets, killed or injured fish, and changes in gauge-pressure readings were called out by swimmers to a data collecting crew in support boats. For purposes of this study, fish were "injured" if they displayed negative buoyancy, turned upside down, or appeared not to have full control over their body orientation for more than a few minutes after a shot. Those showing such behavior for only a minute or so were regarded as "slightly stunned." Damaged targets and killed or injured fish were labeled and saved for further inspection ashore, and in the case of fish, for weighing. Apparently undamaged targets were changed several times during both series of tests and saved for more careful laboratory examination.

(mean=1.9 g, range 1.7-2.2 g, n=5) than the all-yellow one (mean=2.44 g, range 2.1-2.5 g, n=5). We tested the U.S.-made units singly, as simultaneously detonated pairs with each unit of the pair mounted at a different depth, and in clusters of 2 and 3 units each. The other three units used were foreign-made and contained various potassium chlorate ($KClO_3$) explosive mixtures (a more dangerous explosive than potassium perchlorate and illegal in Class-C seal bombs). A plain-cardboard unit from Panama contained an average of 5.76 g, but varied by as much as 1.4 g of explosive (n=3). A red-wrapped unit from Mexico contained 4.02 g (n=1) of explosive, and the charge-weight of an orange unit from Costa Rica averaged 3.82 g (range 3.0-4.1 g, n=12) (Myrick et al. 1990).

Targets for the tests on 26 July consisted of whole, freshly-thawed dolphin carcasses, numerous 16-oz aluminum beverage cans (mounted upside down on a cable they contained air [referred to hereinafter as "air cans"], mounted rightside up they contained water [referred to as "water cans"]), and sealed, plastic 2-liter bottles containing air-filled balloons surrounded by gelatin. The latter targets were intended to simulate lungs (Fig. 2). For the shots on 10 October, targets included maximum-depth diving ("strain-") gauges, heat-mount detectors of different rupture strengths (ordinarily used by cattle ranchers to detect mounting of a cow by a bull), fish cages, each usually with 5 live, swimbladdered fish (mostly Pacific mackeral), and air cans and water cans. Piezoelectric and piezoresistor gauges customarily used for recording instantaneous pressures from large underwater explosions were considered not useful for measuring the explosive force of seal bombs (J. Gaspin, Nav. Surf. Weap. Cent., pers. comm. 1989).

Carcasses were visually inspected externally and sketched before being taken out to the test area. At the end of the test day, carcasses were returned to the La Jolla Laboratory and refrozen for later external comparison with the pre-test sketches and for internal examination for damage.

All mounted targets were inspected by swimmers immediately before and after each shot. Descriptions of damaged targets, killed or injured fish, and changes in gauge-pressure readings were called out by swimmers to a data collecting crew in support boats. For purposes of this study, fish were "injured" if they displayed negative buoyancy, turned upside down, or appeared not to have full control over their body orientation for more than a few minutes after a shot. Those showing such behavior for only a minute or so were regarded as "slightly stunned." Damaged targets and killed or injured fish were labeled and saved for further inspection ashore, and in the case of fish, for weighing. Apparently undamaged targets were changed several times during both series of tests and saved for more careful laboratory examination.

Data on percent fish mortality and injury were plotted by fish weight on a scaled graph originally developed by Yelverton et al. (1975) to predict fish mortality and injury caused by known impulse pressures from large underwater pentolite explosions. We used the graph in reverse, with percent damage to fish by weight used to estimate impulse pressures of our relatively small (i.e., <0.006 kg) explosions. Impluse-pressure estimates (psi-msec) were then used to estimate grades of injury to submerged (non-dolphin) mammals from criteria determined by another study of Yelverton et al. (1973).

From another set of formulae, including the peak pressure formula for TNT (Christian and Gaspin 1974) and curves from Yelverton et al. (1973, 1975) for calculating lethal and safe ranges for terrestrial mammals, we extrapolated hypothetical safe standoff ranges from seal-bomb explosions for dolphins. For these, we assumed 1) that seal bombs exploded underwater were TNT-like in their behavior at close range (Myrick et al. 1990) and, 2) that dolphins would be injured almost as severely as swimming land mammals under similar conditions. We have no data with which to test this latter assumption at present.

RESULTS

Relative Strengths: Damage and Pressures by Bomb Type

Results are presented in Table 1 for the 26 July tests and in Table 2 for the tests conducted on 10 October, but some data were not included. In Table 1, entries for shots 1-4 were omitted because all target-to-bomb distances exceeded 2.0 m and no damage was detected. Shots 14 and 15 were omitted because targets were set 1.5 to 5.6 m from the explosives, no damage was detected, and clusters of three units were used, but not all units in the clusters detonated. In Table 2, shots 19 through 21 were omitted because the explosives malfunctioned. These included the only two detonations attempted of Costa Rican seal bombs.

To explain the organization of the tables, inspection of the damage data in Table 2 will show that columns 1, 3, and 2 under "Damage/Pressure (at distance)" correspond to the target cables 1, 3, and 2 and that rows correspond to the depth order of the targets deployed in the water, identified under "Cables and Targets." For example in Table 2, the first row of damage data for shot 1 (in which a single Class-C bomb was detonated at a depth of 3 m) shows on cable 1, no damage to a heat-mount detector (HL) with (/G) gauge pressure change indicating 1 psi (at 3.3 m). On cable 3, a heat-mount detector (HS) was not damaged (at 3.3 m) and on cable 2 no damage was done to F (fish) at a /G (gauge) pressure-change reading of 1 psi and at a distance of 3.3 m. The depth of this target row from the surface was 1.0 m, and for the second row of targets the depth was 2.5 m. The following description of damage to targets is presented by bomb type.

1. Single Class-C's damaged air cans and fish at ~1.6 m, 3 psi, and fish at 0.0 m, 6 psi.

Data are consistent in showing that single Class-C units damaged air cans at a maximum distance of 1.5-1.6 m (Table 1 shots 5 and 6, Table 2 shots 2-4, 12-14). Can damage was noted when a can's round sides showed signs of deformation into polygonal, flat-sided facets (Fig. 3). Strain-gauge pressure readings available for single Class-C's showed that at 1.3-1.6 m, the maximum distance at which air cans deformed, pressure increases of 3 psi are indicated (Table 2 shots 2-4). No damage was done to any other types of targets, except to fish, at any distance by single Class-C's fired alone. Injury was done to all five of the fish in cages at 0.0 m in shots 12 and 13, and shot 14 killed one and injured the other four at 0.0 m. Shot 12 also injured all five fish at 1.5 m. The only gauge reading we have for these shots at 0.0 m showed a change of 6 psi (shot 14), at 1.5 m (shots 2 and 3) readings showed 3 psi. Although the pressures were larger closer to the explosions, as would be expected, it seems clear from the psi values that the pressure readings were only relative measurements.

2. Simultaneous detonation of Class-C pairs damaged water and air cans and fish at 0.6 m (6-7 psi) but did no damage at 1.0 m.

In shots 5-11 in the October 10 tests (Table 2), a pair of Class-C units, one at 1.0 m, the other at 3.0 m, was detonated simultaneously. This was done to try to simulate more closely the actual situation in a purse-seine set, in which at least two seal bombs thrown separately may detonate at different depths at once. In these simultaneous shots, a heat-mount detector was slightly damaged at 1.3 m -- perhaps an artifact (shot 6). A water can and 3 air cans were damaged at 0.5-0.6 m (shots 8-11). Maximum readings at 0.5-1.0 m, in some of these shots show increased pressures of 7 psi (shots 5, 7, and 8). However, in two shots (5 and 6) water cans at 1.1 m were undamaged and in shot 11, 3 air cans at 1.0-1.1 m were not damaged.

This apparent inconsistency, here and elsewhere, between damage and pressures at distance was likely due to strong, but highly variable (shot-specific), directionality in the explosive force. It is conceivable also that the pressure waves of the two separate but simultaneous explosions truncated each other at about 1.0 m. This would be similar to the situation in which the surface reflection of the pressure wave from an underwater explosion interferes with (i.e., "cuts off") the outward movement of the pressure wave from source when the two intersect (e.g., as noted by Gaspin 1983). Thus, as it seems from the simultaneous shots, the energy released may be as strong as or stronger than that from a single Class-C unit, but it may attenuate or truncate in a shorter distance.

3. Clusters of Class-C's damaged air cans at 1.5 m, water cans at 2.1 m, and ruptured heat-mount detectors at 0.0 m.

On 10 October, two tests with clusters of 2 Class-C units (Table 2 shots 15 and 16) detonated at a depth of 1.0 m caused moderate to heavy damage to air cans at 1.5 m. They caused only slight damage to one air can and no damage to five air cans positioned at the surface, 1.0 m from the cluster. In each test, a heat-mount detector was completely ruptured and all five fish in a cage were injured at 0.0 m. In addition, in shot 16, one fish was killed and the other four injured in a cage at 1.5 m, but fish at this position were not affected in shot 15.

In two tests of clusters of 3 Class-C units on 26 July, damage was done to only one air can and one water can (Table 1 shots 16 and 17). The air can was heavily damaged at 0.6 m (shot 16), but no damage was done to an air can at 0.7 m (shot 17). Shot 17 moderately damaged a water can at 2.1 m, but no damage was done to water cans at 0.5 and 1.6 m in shot 16, in which the bomb was detonated at the surface. Apparently much of the energy from shot 16 was vented directly into the air.

4. Panamanian bombs extended the range of damage to air cans to 1.8 m, water-can damage to 2.0 m, bottle damage to 1.5 m, and fish kill to 1.8 m, and at 0.6 m caused the only damage done to a dolphin carcass.

Single Panamanian bombs caused moderate to heavy damage to air cans as distant as 1.8 m (Table 2 shots 17 and 18), but no damage to an air can at 2.1 m (Table 1 shot 19). Panamanian shots heavily damaged a water can at 1.6 m (Table 1 shot 18) and caused very slight damage to one water can and no damage to a second water can at 2.0 m (Table 2 shots 17 and 18), and no damage to two water cans at 2.1 m (Table 1 shot 18).

Four live fish showed no effects of a Panamanian unit exploded at 2.0 m in shot 18 (Table 2). The same four were killed outright at 1.8 m in shot 23 after having been slightly by a Mexican unit (in shot 22) at 2.0 m. We noted that the kill from shot 23 could have been potentiated by the two earlier shots. According to M. Wiley (U. of MD, pers. comm., 1989), "any fish that shows signs of having been stunned by an underwater explosion is also likely to have suffered swimbladder damage."

A Panamanian bomb was the only type of unit that damaged a bottle or a dolphin carcass. One balloon was deflated in one bottle at 1.6 m and a 5 x 7-cm jagged wound 4-cm deep was incurred above the right shoulder of a carcass at 0.6 m (Table 1 shot 18).

Subsequent examination of the carcass (Fig. 4) disclosed that the right shoulder blade had been shattered, the diaphysis of the

humerus fractured, and the subscapular and intercostal musculature pulverized, but no penetration was made into the pulmonary cavity. Examination of the cranial bones revealed fractures to hamular processes of both pterygoids and a fractured left temporal bone. No internal damage was found, except possible evidence of compression on the right lung by the first right rib, thought perhaps to have been associated with the shoulder-blast damage. Participants in the examination of the specimen could not attribute cause of the cranial damage to test explosions partly because the temporal fracture was on the side opposite the shoulder damage. Further, there was no certainty that the cranial damage was not incurred elsewhere since postmortem history of the specimen was unknown.

5. Red Mexican seal bombs caused air-can damage at 1.1 m and slight water-can damage and slightly stunned fish at 2.0 m.

Two tests were conducted on red Mexican units (Table 1 shot 20 and Table 2 shot 22). The only damage done by shot 20 was to an air can at 0.7 m. Shot 22 slightly damaged water cans at 1.0 and 2.0 m and caused moderate damage to an air can at 1.1 m. However, no damage was done to air cans positioned at 0.0-m depth and 1.4 to 1.5 m from the explosion in shot 22. Examination of the areas of damage among the deployed targets (as reconstructed from the target rows and columns in Table 2) suggests that most of the explosive force was directed downward and toward target cable 1.

As mentioned under Panamanian-bomb damage (4. above), the slight stunning of the four fish at 2.0 m in this shot may have contributed to the kill of all four in shot 23. By the same argument, shot 18 (Panamanian unit), the first shot on this fish sample, may have contributed to the slight stunning of the fish by the shot with the Mexican unit. Thus, the shots 18, 22, and 23 may all have had a cumulative effect that finally resulted in the 100% kill.

6. Synopsis.

Considering the damage done to targets and the obviously low associated peak pressures indicated, it was apparent that the gauges we used were only relatively responsive to instantaneous shock-wave pressures and the heat-mount detectors less so. A much better indicator of relative bomb strength was the actual physical damage incurred by specific types of targets at distance. Despite the repeated problem of directionality in the energy of the explosives, damaging pressure to the most sensitive targets, air and water cans, did not extend far beyond 2.0 m.

For Single Class-C units the likely maximum range for damage to air cans must be less than 2.0 m. For the Panamanian unit, the

most powerful explosive we tested, maximum air-can and water-can damage range should be no farther than 2.5 m. The range for 3-unit clusters of Class-C's is no greater, and probably is somewhat less than that of the Panamanian unit. Our two tests on the red units from Mexico indicated that they were weaker than clustered Class-C's. Simultaneous detonation of two separate Class-C units seemed to produce pressures stronger at close range than a single Class-C unit, but had less power than that of a cluster. Thus, we have by bomb type, maximum ranges for air-can damage:

Bomb Type	Air-Can Damage at Maximum Distance	
C simultaneous	?< 2.0 m	
Class-C single	~ 2.0 m	
Red Mexican	< 2.5 m	(weaker than C clusters)
C clusters	< 2.5 m	
Panamanian	~ 2.5 m	

Determining Impulse Pressures from Fish Damage

1. Single Class-C units.

Data on fish killed and injured in single Class-C units and simultaneous explosions at different depths of two single Class-C units are given in Table 3. Those data from shots in which fish were retrieved and weighed were plotted on the Yelverton et al. (1975) scaled graph to determine impulse pressure (Fig. 5). The seven data points from five shots (8-11) using two simultaneous explosions and two shots of single units (12 and 14) fall between 1 and 2 bars per millisecond (msec), or between 15 psi-msec and 26 psi-msec (Fig. 5, modified from Yelverton et al. 1975). Comparing the data in Table 3 with the data points and impulse pressure intercepts, it is possible to see that shots 12 and 14 of single units developed approximately 15 psi-msec impulse pressure at or very near the explosion source. Data from simultaneous explosions of single units at different depths show that shots 8 and 10 generated impulse pressures of 18 to 20 psi-msec at 0.5 to 0.7 m from source and shot 11, in which mortality of fish was 2 out of 5 (40%), produced pressures of about 22 psi-msec at 0.7 m.

2. Other units.

Referring to Table 2, in which fish mortality and injury is indicated for other types of units, if we assume that the fish used in the tests of other units were within the same range of weights as those plotted in Fig. 5, data points would indicate the following:

1. clustered units of 2 Class-C's might generate impulse pressures of 15 to 21 psi-msec at 1.5 m (shot 16),
2. a red Mexican unit might produce 15 psi-msec at 2.0 m (shot 22), and

3. a Panamanian unit might produce between 18 and 21 psi-msec at 1.8 m (shot 23).

These rough measures are fairly consistent with the order of bomb strengths indicated by damage to cans, as outlined in the synopsis (above).

DISCUSSION

Explosion Pressures (after Christian and Gaspin 1974, p. 31 ff.)

The shock wave from an underwater detonation of a high velocity explosive is characterized in terms of shock wave peak pressure (Pmax, the steep front of the explosion disturbance that travels outward from the source) and shock wave impulse pressure (I, essentially all of the pressure produced by the explosion over time). Pmax is explosive- and charge-weight specific, with TNT used as the standard. The general formula is:

$$\text{Pmax (in psi)} = A \left(\frac{W^{1/3}}{R} \right)^{a} \qquad (1)$$

where W is the weight of the charge in pounds, R is the distance from the charge in feet, "A" is a constant for TNT-like explosives (21,600), and "a" is a factor dependent on the type of explosive (for TNT it is 1.13).

Impulse pressure is the integral of the pressure-time curve behind the pressure front as it decays, almost exponentially, over time. It is calculable for an explosive whose decay rate is known.

For TNT the impulse of the shock up to time t_s is:

$$I(\text{in psi-msec}) = 1300\ W^{0.64}\ R^{-0.91}\ [1-e^{Q}] \qquad (2)$$

where $Q = -16.67\ t_s\ W^{-0.26}\ R^{-0.18}$.

Most authorities agree that the strength of the impulse pressure in an underwater explosion is more important than the peak pressure in terms of injury and lethality. For example, in the words of Christian and Gaspin (1974, p. 1), "tests with submerged animals [mostly by Richmond et al. (1970)], primarily sheep, have shown that there is no physical damage [from underwater explosions] provided the impulse does not exceed 5.5 psi-milliseconds while the peak pressure does not exceed about 125 psi...Actually, no internal injuries ever occurred when the impulse was as low as 2 psi-milliseconds even with peak pressures as high as several hundred psi."

Injury from Impulse Pressures

The necessary measurements for potassium perchlorate and potassium chlorate mixtures have not been made to enable calculations of specific Pmax or I for these explosives (except as estimated on the basis of assumed TNT-equivalent ratings [Myrick et al. 1990]). However, several examples may give a rough idea of what the impulse pressures, obtained from our data in the fish damage formula, may mean in terms of potential injury to submerged (non-dolphin) mammals.

Navy guidelines for minimum risk of acceptable injury to unprotected human swimmers, is an impulse pressure equal to or less than 10 psi-msec (Gaspin 1983)(see our Fig. 5). We note here that these guidelines for impulse pressure are not the same as the "swimmer safe" guidelines, which uses 5.5 psi-msec corrected downwards for maximum safety to 2.0 psi-msec (Christian and Gaspin 1974).

Navy SEALS, who in the past, have used M-80s (containing 3.0 g of potassium perchlorate mixture identical in composition to the U.S.-made Class-C seal bomb [Conkling 1985]) for emergency backup communication in the water, had standing instructions prohibiting their use within 10 feet (3.0 m) of SEAL-team members (Cmdr. W. McNally, Chief, U.S. Navy SEALS, San Diego CA, pers. comm. 1989). The unit used by the SEALS differed from the Class-C unit (which generates at least 15 psi underwater impulse pressure near source) in three features. It contained approximately 0.5 g more explosive, it had no weighting material, and it was wax-dipped to make it float. Thus, the 3-m restriction for the Navy's unit was imposed despite that most of its potentially damaging impulse energy vents directly into the air.

In addition, the Yelverton et al. (1973, Table 10) underwater-blast criteria for (terrestrial) mammals diving beneath the water surface gives the following predicted results:

Impulse Pressure (psi-msec)	Criteria
40	No mortality. High incidence of moderately severe blast injuries.
20	High incidence of slight blast injuries.
10	Low incidence of trivial blast injuries.
5	Safe level. No injury.

The Yelverton et al. (1973, Fig. 16) data show that moderately severe blast injury (i.e., ~40 psi-msec impulse pressure) includes slight to extensive lung hemorrhage and mild to severe contusion

to the GI tract. Slight blast injury, at ~20 psi-msec, includes petechia to slight lung hemorrhage and no GI-tract damage to mild and severe contusions of the GI tract. Trivial injury (at ~10 psi-msec) includes no lung hemorrhage to petechial lung damage and no damage of the GI tract to petechia and mild contusions.

With reference to the data points in our Fig. 5, generated from fish-damage from Class-C seal bomb tests, the Yelverton et al. (1973) blast criteria are indicated in the right margin of the figure. They show (arrows) that impulse pressures indicated by our data would cause low incidence of trivial blast injuries to high incidence of slight blast injuries to submerged terrestrial mammals. Thus, if our method of addressing the problem has validity, we have some answers to our first question and to the first part of our second question concerning seal-bomb-blast pressure and injury to submerged land mammals.

Estimation of "Safe Ranges"

"What are safe distances" for mammals to be protected from direct physical injury from seal-bomb explosions? To answer this, we again followed Yelverton et al. (1975) whose curves for calculating lethal (and safe) ranges for submerged mammals are most useful. The best explanation of these calculations is by Wright (1982). The calculations require the impulse pressure to be selected from the Yelverton et al. (1973) table of blast injury criteria (presented above under "Injury from Impulse Pressure") for the amount of protection desired. The second step is to determine the scaled impulse by dividing the desired impulse value by the cube root of the charge weight. The third step is to calculate "parameter A: "

$$A = \frac{\text{target depth (m) x bomb depth (m)}}{\text{charge weight (kg)}^{2/3}} \qquad (3)$$

Fourth, from the curves developed by Yelverton et al. (1975) (our Fig. 6) a best-fit curve is selected to the calculated value of "A." Then, using the curve or range of curves, one finds the intersection of the curve(s) with the scaled impulse (from step 2) to determine the scaled range on the left margin of the graph. Finally, the standoff range (m) is calculated by multiplying the scaled range by the cube root of the charge weight.

To compare our test damage and impulse data with the Yelverton et al. (1973) standoff-range criteria, we determined curve intersections for all 4 impulse pressure levels, using curves calculated from seal-bomb charge-weights of 2, 2.5, 3, and 4 g and target-bomb depths of 1-1, 1-3, 2.5-1 and 2.5-3 m (Fig. 6). According to these results (arrows, right-hand margin, Fig. 6), a 4-g seal bomb detonated at 1-3 m depth on a mammal at 1-2.5 m depth, should cause no injury if it is more than 8.0 m from the source. Trivial injury should not occur at distances greater than 3.2 m, slight injury not

beyond 1.6 m, and severe injury should not occur at distances greater than 0.8 m. A 2.5-g (Class-C-weight) explosive at a 1-3-m depth on a mammal 1-2.5-m deep should cause no injury at 7.0 m, it should not cause trivial injury beyond about 2.8 m, slight injury beyond 1.4 m, and moderately severe injury farther than 0.7 m.

A 2.3-g charge, the standard weight given by the manufacturer for the current U.S. seal bomb (Myrick et al. 1990), should cause moderately severe injury only within 0.53 m, slight injury within 1.1 m, trivial injury within 2.3 m (Fig. 7). If the explosive mixture of the U.S. unit produces only 80% of the pressure of an equivalent charge of TNT, as is suggested by Myrick et al. (1990) following McIntyre (1980), a submerged mammal would sustain moderately severe injury at 0.5 m, slight injury at 1.0 m, and trivial injury at 2.2 m. The safe standoff distance in such a case would still be about 4.3 m (Fig. 7).

These standoff estimates appear to correspond very well with data from our tests in which Class-C units killed fish within 0.7 m and injured fish within 1.6 m and damaged cans at a range of just less than 2.0 m. Panamanian units (averaging 5.76 g, varying by at least +/- 1.4 g) caused a 100 % fish kill (probably with some help from two previous shots) at 1.8 m, damaged cans at 1.8-2.0 m, and produced a severe wound in a carcass at 0.6 m.

Are Seal-bomb Data Applicable?

Although most underwater explosion-injury measurements have been made on fish or mammals using large charges of high-velocity explosives (i.e., 0.5 to >500 kg of TNT, pentolite, or related materials), at least three published reports exist in which firecracker-size charges were used on mammals. Considerable doubt remains as to whether impulse pressure and standoff-distance conversions, established on the basis of large charges of high explosives, are applicable to explosions of seal-bomb magnitudes. Thus, it is of interest to examine these three reports. We summarize them for reader information, with only minimal comment (indicated by brackets).

Hirsch and Ommaya (1972) retrospectively studied an accidental death of a submerged human swimmer, who was killed apparently by an M-80 (containing 3.0 g of explosive) that exploded underwater near his head. The explosion ruptured both eardrums, herniated brain tissue through ruptured areas in the cribriform plates, fractured cranial bones including the wings of the sphenoid and the left petrosal, and caused a 1.5-cm-deep wound above the scapula [very similar in appearance to the wound caused to the dolphin carcass by the Panamanian unit at 0.6 m]. The authors' reconstruction of the event, from eye-witness accounts, indicated that the victim was one foot (0.3 m) or less below the firework when it exploded. They used the TNT formula to estimate a Pmax of

when it exploded. They used the TNT formula to estimate a Pmax of 3,260 psi at that lethal distance.

Andersen and Løken (1968) experimented with paired and staggered charges of 1 g of Tetryl (a TNT-like explosive) on 120- to 250-g rats with bodies submerged below the shoulders at 0.8 m from the explosions. They obtained a 200% increase in lethality in some samples with two detonations staggered at 8 to 25 μsec. [This would be somewhat similar to seal bombs thrown and detonated in quick succession.] This compared with 30% mortality using simultaneous detonations with no delay and 55% mortality when only a single 1-g charge was detonated. [No pressure measurements were given, but using the TNT formula for Pmax, 1 g should yield something on the order of 1,125 psi at 0.8 m.]

Friedell and Ecklund (1943) set off 2.3-g charges of fulminate of mercury (blasting caps) and 60-120-g charges of TNT underwater on guinea pigs and rabbits submerged from the neck down. Charges were placed at different distances from the animals in a steel 8 x 6-foot (2.44 x 1.8-m) tank containing about 4 feet (1.22 m) of water. Double blasting caps detonated within 18 inches (0.46 m) caused hemorrhaging and death in unprotected animals. But animals subjected to explosions at 20-24 inches (0.51-0.61 m), including one triple charge, recovered. [According to our data plots on the Yelverton et al. (1975) curves, a 2.3-g seal bomb should cause moderately severe damage to a mammal at between 0.5 and 0.6 m, 0.5 m if 80% TNT equivalency is used (Fig. 7).]

CONCLUSIONS

Based on the assumption that seal-bomb data from the open-water tests bear some relationship (e.g., 80% equivalency) to results from other forms of explosives, it is our view that the e xtrapolations made for mammal standoff ranges for seal-bomb explosions are approximately correct. However, lacking the direct data from a more parsimonious approach, it has not been determined in this study whether these safe and injury ranges are entirely applicable to dolphins.

As Hill (1978, p. 1) has pointed out, "since [the criteria established by Yelverton et al. 1973] were determined using relatively small (5-40 kg) land mammals as subjects, they probably include a `built-in' safety factor when used to predict damage to [typically larger, except for dolphin calves] marine mammals." Almost nothing is known with respect to the specific problem of possible blast injuries to dolphins from underwater explosions. Considering the unique anatomical and physiological adaptations that allow dolphins to withstand strong, rapid pressure changes while diving, we might expect that dolphins may be affected differently than other mammals by pressure waves from explosions (see also Hill 1978).

Nevertheless, from a conservative point of view, the results of these studies suggest that the use of Panamanian-type seal bombs will cause additional dolphin mortality when detonated at close range. Furthermore, while use of single U.S.-made Class-C units are unlikely to cause direct mortality, there is little doubt that these units can cause injury when detonated underwater within 4.0 m from a dolphin or other swimming mammal.

Hazardous effects of seal bombs on dolphins other than direct injury have not been addressed in this study. It is not clear how dolphins may be affected by the noise or flash components of a seal-bomb explosion, or by long-term or repeated short-term exposure to explosions of seal bombs of various types (Majors and Myrick, 1990).

ACKNOWLEDGEMENTS

We thank the many people who contributed their time, effort, and resources to help make this study successful. D. Losey was instrumental in helping us access the literature. Those who assisted in the open-water experiments included: J. Stewart, "Moe" Jarvis, R. Robinson, E. Stalnaker, J. Gaspin, B. Hofman, R. Rule, R. Tarpley, K. Mahoney, D. Bratten, K. Eckert, C. Lockyer, B. Chou, J. Bortniak, S. Sexton, D. DeMaster, W. Perrin, J. Hunter, M. Hall, D. Hanan, A. Hudoff, D. Holts, A. Coan, A. Jackson, M. Trianni, A. Dizon, J. Kashiwada, M. Bones, D. Roll, A. Bright, P. Akin, S. Chivers, K. Peltier, A. Hohn, A. Majors, P. Smith, S. Reilly, and L. Robertson. The figures were masterfully prepared by H. Orr. C. Glick assisted with plots and calculations. The manuscript was improved measurably by comments from D. DeMaster, A. Dizon, C. Lockyer, K. Eckert, B. Remington, and C. Glick and subsequently by the participants of the Workshop on Seal Control Devices, held at the La Jolla Laboratory on 27-29 November 1989. C. Ratcliffe helped to prepare iterations of the manuscript. D. Stroh helped in proofing the copy.

LITERATURE CITED

Awbrey, F. and J.A. Thomas. 1987.
Measurements of sound propagation from several acoustic harassment devices. Pp. 85-104. In: B.R. Mate and J.T. Harvey (eds.), Acoustical deterrents in marine mammal conflicts with fisheries. Oregon State Univ. Publ. ORESU-W-86-001.

Andersen, P. and S. L0ken. 1968.
Lung damage and lethality by underwater detonations. Acta. Physiol. scand. 72:6-14.

Cassano, E.R., A.C. Myrick, Jr., C.B. Glick, and R.C. Holland. 1990.
The use of seal bombs on dolphins in the eastern tropical Pacific yellowfin tuna purse-seine fishery. SWFC Admin. Rept. LJ-90-09

Christian, E.A. and J.B. Gaspin. 1974.
Swimmer safe standoffs from underwater explosions. Navy Science Assistance Program Project No. PHP-11-73, Rept. No. NOLX 80. 48 p.

Conkling, J.A. 1985.
Chemistry of pyrotechnics, basic principles and theory. Marcel Dekker Inc., New York. 190 p.

Gaspin, J.B. 1983.
Safe swimmer ranges from bottom explosions. Nav. Surf. Weap. Cen. Tech. Rept. 83-84. 51 p.

Friedell, F.T. and A.M. Ecklund. 1943.
Experimental immersion blast injury. U.S. Nav. Med. Bull. 41 (March): 353-363.

Hill, S.H. 1978.
A guide to the effects of underwater shockwaves on Arctic marine mammals and fish. Pacific Marine Science Rept 78-26. Institute of Ocean Sciences, Patricia Bay, Sidney, B.C. 50 p.

Hirsch, A.E. and A.K. Ommaya. 1972.
Head injury caused by underwater explosion of a firecracker. J. Neurosurg. 37 (1):95-99.

Holliday, D.V. 1972.
Resonance structure in echoes from schooled pelagic fish. J. Acoust. Soc. Amer. 51(4) part 2: 1322-1331.

Majors, A.P. and A.C. Myrick, Jr. 1990.
Effects of noise on animals: implications for dolphins exposed to seal bombs in the eastern tropical Pacific purse-seine fishery. An annotated bibliography. SWFC Admin. Rept. LJ-90-06.

McIntyre, F.L. 1980.
A compilation of hazard and test data for pyrotechnic compositions. U.S. Armament Research and Development Command. Large Caliber Weapon Systems Lab., Dover, NJ. Contract Rept. ARLCD-CR-80047 (AD-E400-496).

McNeeley, R. L. 1961.
The purse seine revolution in tuna fishing. Pacific Fishermen (June, 1961). 58 p.

Myrick, A.C., Jr., M. Fink, and C.B. Glick. 1990.
Identification, chemistry, and behavior of seal bombs used to control dolphins in the yellowfin tuna purse-seine fishery in the eastern tropical Pacific: potential hazards. SWFC Admin. Rept. LJ-90-08.

Perrin, W.F. 1969.
Using porpoise to catch tuna. World Fishing 18 (6): 42-45.

Richmond, D.R., J.T. Yelverton, C.S. Gaylord, and E.R. Fletcher. 1970.
Underwater blast studies with animals. Defense Atomic Support Agency Rept. No. 2463 (not seen).

Wright, D.G. 1982.
A discussion paper on the effects of explosives on fish and marine mammals in the waters of the Northwest Territories. Can. Tech. Rept. Fish. Aquat. Sci. 1052. 1-16.

Yelverton, J.T., D.R. Richmond, E.R. Fletcher, and R.K. Jones. 1973.
Safe distance from underwater explosions for mammals and birds. Defense Nuclear Agency, Dept. of Defense, Wash., D.C., Tech. Rept. DNA 3114 T. 67 p.

Yelverton, J.T., D.R. Richmond, W. Hicks, K. Sanders, and E.R. Fletcher. 1975.
The relationship between fish size and their response to underwater blast. Defense Nuclear Agency, Dept. of Defense, Wash., D.C., Topical Rept. DNA 3677 T. 42 p.

Table 1. Results of open-water tests of seal bombs on targets (July 26, 1989). (CG Sing=single green-labeled Class C, C Clstr=cluster of 3 Class C's, Pan=Panamanian Panamanian, R Mex=red Mexican, air=air cans, wat=water cans, bot=bottles, carc=carcasses, +, ++, +++=slight, moderate, heavy damage).

Shot	Type Bomb	Bomb Depth (m)	Cables and Targets 1	3	2	Target Depth (m)	Damage (at distance) 1		3		2
5	CG Sing	3	air	carc	wat	0	--	(3.3)	--	(3.3)	-- (3.3)
			wat	bot	carc	1	--	(2.5)	--	(2.5)	-- (2.5)
			carc	air	bot	2.5	--	(1.6)	+	(1.6)	-- (1.5)
			bot	wat	air	5.0	--	(2.4)	--	(2.4)	-- (2.4)
6	CG Sing	0	same as above				++	(1.6)	--	(1.6)	-- (1.5)
							--	(2.1)	--	(2.1)	-- (1.8)
							--	(3.3)	--	(3.3)	-- (3.1)
							--	(5.6)	--	(5.6)	-- (5.4)
7	CG Sing	0	same as above				--	(1.6)	--	(1.6)	-- (1.5)
							--	(2.1)	--	(2.1)	-- (1.8)
							--	(3.3)	--	(3.3)	-- (3.1)
							--	(5.6)	--	(5.6)	-- (5.4)
8	CG Sing	3	same as above				--	(3.3)	--	(3.3)	-- (3.3)
							--	(2.4)	--	(2.4)	-- (2.4)
							--	(1.6)	--	(1.6)	-- (1.5)
							--	(2.4)	--	(2.4)	-- (2.4)
9	CG Sing	0	same as above				--	(0.6)	--	(0.6)	-- (0.5)
							--	(1.6)	--	(1.6)	-- (1.3)
							--	(3.1)	--	(3.1)	-- (2.9)
							--	(5.4)	--	(5.4)	-- (5.3)
10	CG Sing	3	same as above				--	(3.1)	--	(3.1)	-- (3.1)
							--	(2.1)	--	(2.1)	-- (2.1)
							--	(0.7)	--	(0.7)	-- (0.6)
							--	(2.1)	--	(2.1)	-- (2.1)
11	CG Sing	0	same as above				--	(0.5)	--	(0.5)	-- (0.0)
							--	(1.1)	--	(1.1)	-- (1.0)
							--	(2.6)	--	(2.6)	-- (2.5)
							--	(5.1)	--	(5.1)	-- (5.0)
12	CG Sing	3	same as above				--	(3.1)	--	(3.1)	-- (3.0)
							--	(2.1)	--	(2.1)	-- (2.0)
							--	(0.7)	--	(0.7)	-- (0.5)
							--	(2.1)	--	(2.1)	-- (2.0)
13	CG Sing	3	same as above				--	(3.1)	--	(3.1)	-- (3.0)
							--	(2.1)	--	(2.1)	-- (2.0)
							--	(0.7)	++	(0.7)	-- (0.5)
							--	(2.1)	--	(2.1)	-- (2.0)
16	C Clst	0	same as above				+++	(0.6)	--	(0.6)	-- (0.5)
							--	(1.6)	--	(1.6)	-- (1.3)
							--	(3.1)	--	(3.1)	-- (2.9)
							--	(5.4)	--	(5.4)	-- (5.3)
17	C Clst	3	same as above				--	(3.1)	--	(3.1)	-- (3.1)
							++	(2.1)	--	(2.1)	-- (2.1)
							--	(0.7)	--	(0.7)	-- (0.6)
							--	(2.1)	--	(2.1)	-- (2.1)
18	Pan	0	same as above				+++	(0.6)	+++	(0.6)	-- (0.5)
							+++	(1.6)	+	(1.6)	-- (1.3)
							--	(3.1)	--	(3.1)	-- (2.9)
							--	(5.4)	--	(5.4)	-- (5.3)
19	Pan	3	same as above				--	(3.1)	--	(3.1)	-- (3.1)
							--	(2.1)	--	(2.1)	-- (2.1)
							--	(0.7)	+++	(0.7)	-- (0.6)
							--	(2.1)	--	(2.1)	-- (2.1)
20	R Mex	3	same as above				--	(3.1)	--	(3.1)	-- (3.1)
							--	(2.1)	--	(2.1)	-- (2.1)
							--	(0.7)	+++	(0.7)	-- (0.7)
							--	(2.1)	--	(2.1)	-- (2.1)

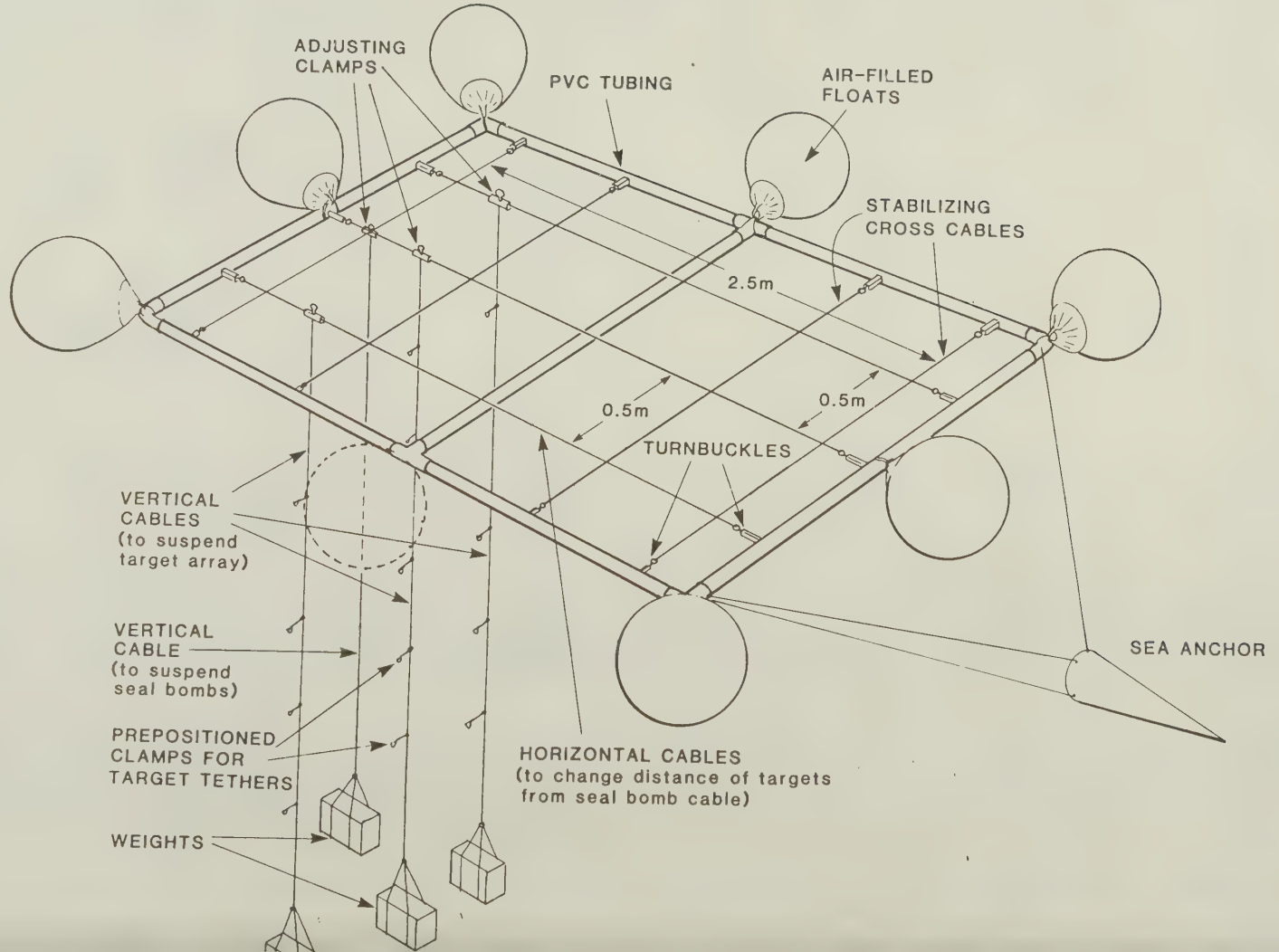
labeled Class C, CG Clstr=cluster of 2 green-labeled Class C, Pan=Panamanian, R Mex=red Mexican, H, HL, HS=Heat-mount detect
fish, G=diver strain gauge, wat=water can, air=air can, /#=pressure difference in psi recorded by gauge, K=fish killed, I=f
+, ++, +++=slight, moderate, heavy damage, bold face=change in target array, *=failed to get guage reading, $ broken gauge

Shot	Type Bomb	Bomb Depth (m)	Cables and Targets 1	3	2	Target Depth (m)	Damage/Pressure (at distance) 1		3		
1	CYSing	3	HL/G	HS	F/G	1	-/1	(3.3)	--	(3.3)	-/1
			H	air	wat	2.5	--	(2.6)	-/.5	(2.6)	--
2	CYSing	3	same as above				-/0	(2.5)	--	(2.5)	-/3
							--	(1.6)	++/3	(1.6)	--
3	CYSing	3	same as above				-/1	(2.5)	--	(2.5)	-/1
							--	(1.6)	++/3	(1.6)	--
4	CYSing	3	same as above				-/1	(2.3)	--	(2.3)	-/1
							--	(1.3)	++/3	(1.3)	--
5	CGSing	1	HL/G	HS	F/G	1	-/1	(1.3)	--	(1.3)	-/7
(simultaneous)		3	H	F/G	wat	2.5	--	(1.3)	-/0	(1.3)	--
6	CGSing	1	same as above				-/0	(1.3)	+	(1.3)	-/4
(simultaneous)		3					--	(1.3)	-/0	(1.3)	--
7	CGSing	1	same as above				-/0	(0.6)	--	(0.6)	-/7
(simultaneous)		3					--	(0.7)	-/0	(0.7)	--
8	CGSing	1	same as above				-/1	(0.6)	--	(0.6)	1K4I/7
(simultaneous)		3					--	(0.7)	-/1	(0.7)	++
9	CGSing	1	HL/G	HS	F/G	1	-/0	(0.6)	--	(0.6)	5I/5
(simultaneous)		3	H	F/G	air	2.5	--	(0.7)	-/1	(0.7)	++
10	CGSing	1	air	air	air	0	--	(1.1)	--	(1.1)	--
(simultaneous)		3	HL/G	HS	F/G	1	-/2	(0.6)	--	(0.6)	1K4I/*
			H	F/G	air/HS	2.5	--	(0.7)	1K4I/1	(0.7)	++
11	CGSing	1	same as above				--	(1.1)	--	(1.1)	--
(simultaneous)		3					-/2	(0.5)	--	(0.5)	5I/$
							--	(0.7)	2K3*	(0.7)	++/-
12	CGSing	1	air	air	air		--	(1.1)	--	(1.1)	--
			HL/G	HS	F		-/2	(0.5)	+	(0.5)	5I
			H	F(3)	air/HS		--	(1.6)	3I	(1.6)	+/-
13	CGSing	1	same as above			0	--	(1.1)	+	(1.1)	--
						1	-/2	(0.5)	--	(0.5)	5I
						2.5	--	(1.6)	--	(1.6)	++/-
14	CGSing	1	same as above				--	(1.0)	+	(1.0)	--
							++/6$	(0.0)	--	(0.0)	1K4I
							--	(1.5)	--	(1.5)	++/-
15	CGClstr	1	air	air	air	0	--	(1.0)	+	(1.0)	--
			HL/air	HS	F	1	+++/++	(0.0)	--	(0.0)	5I
			H	F(5)	air/HS	2.5	--	(1.5)	--	(1.5)	+++/-
16	CGClstr	1	same as above				--	(1.0)	--	(1.0)	--
							+++/++	(0.0)	--	(0.0)	5I
							--	(1.5)	1K4I	(1.5)	++/-
17	Pan	1	air	air	air	0	--	(1.5)	+++	(1.5)	--
			HL/air	HS	wat	1	+++/++	(1.1)	--	(1.1)	--
			H/wat	G	air/HS	2.5	-/-	(2.0)	-/1	(2.0)	+++/-
18	Pan	1	air	air	air	0	--	(1.5)	++	(1.5)	--
			HL/air	HS	wat	1	+++/+	(1.1)	--	(1.1)	--
			H/wat	F(4)/G	air/HS	2.5	-/+	(2.0)	-/2	(2.0)	++/-
22	RMex	1	same as above				--	(1.5)	--	(1.5)	--
							-/++	(1.1)	--	(1.1)	+
							-/+	(2.0)	4I/0	(2.0)	--
23	Pan	1	same as above				++	(1.1)	++	(1.1)	++
							-/+++	(0.7)	--	(0.7)	--
24	Pan	1	air	air	air	0	+	(1.1)	++	(1.1)	++
			HL/air	HS	wat	1	++/+++	(0.5)	+	(0.5)	++
			H/wat	G	HS	2.5	-/-	(1.6)	-/0	(1.6)	--

Table 3. Fish mortality, injury, and weight (g) in open-water tests with single (S) and simultaneously detonated pairs (SS) of Class-C seal bombs, conducted 10 October 1989.

Bomb Type	Bomb Depth (m)	Cage Depth (m)	Cage Distance	Fish Kill	%	Wt	Injured	%	Wt
SS	1/3	1	0.5	1	20	183	4	80	154 321 73 133
SS	1/3	1	0.5	-			5	100	
SS	1/3	1	0.5	2	20	158	4	80	149 143 161 141
		2.5	0.7	1	20	148	4	80	152 192 174 68
SS	1/3	1	0.0	-			5	100	143 148 166 138 135
		2.5	0.7	1	40	143 145	3	60	146 169 141
S	1	1	0.0	-			5	100	133 148 157 140
		2.5	1.6	-			3	100	
S	1	1	0.0	-			5	100	
S	1	1	0.0	1	20	65	4	80	138 144 144 150

Figure 1 Floating target array used to test damage from underwater detonations of seal bombs.



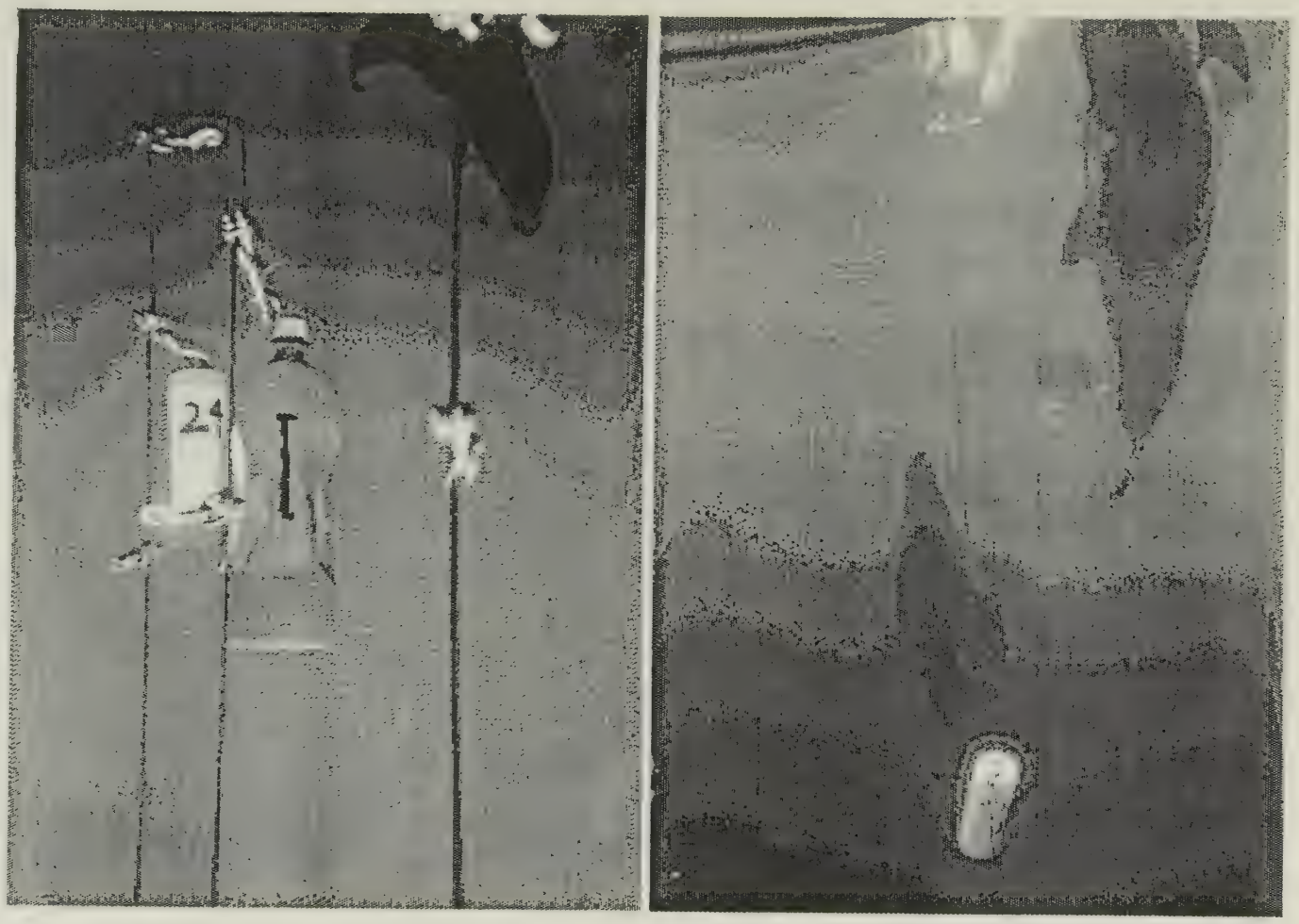


Figure 2 Underwater deployment of bottles, cans, and dolphin carcasses as targets to test seal-bomb damage.

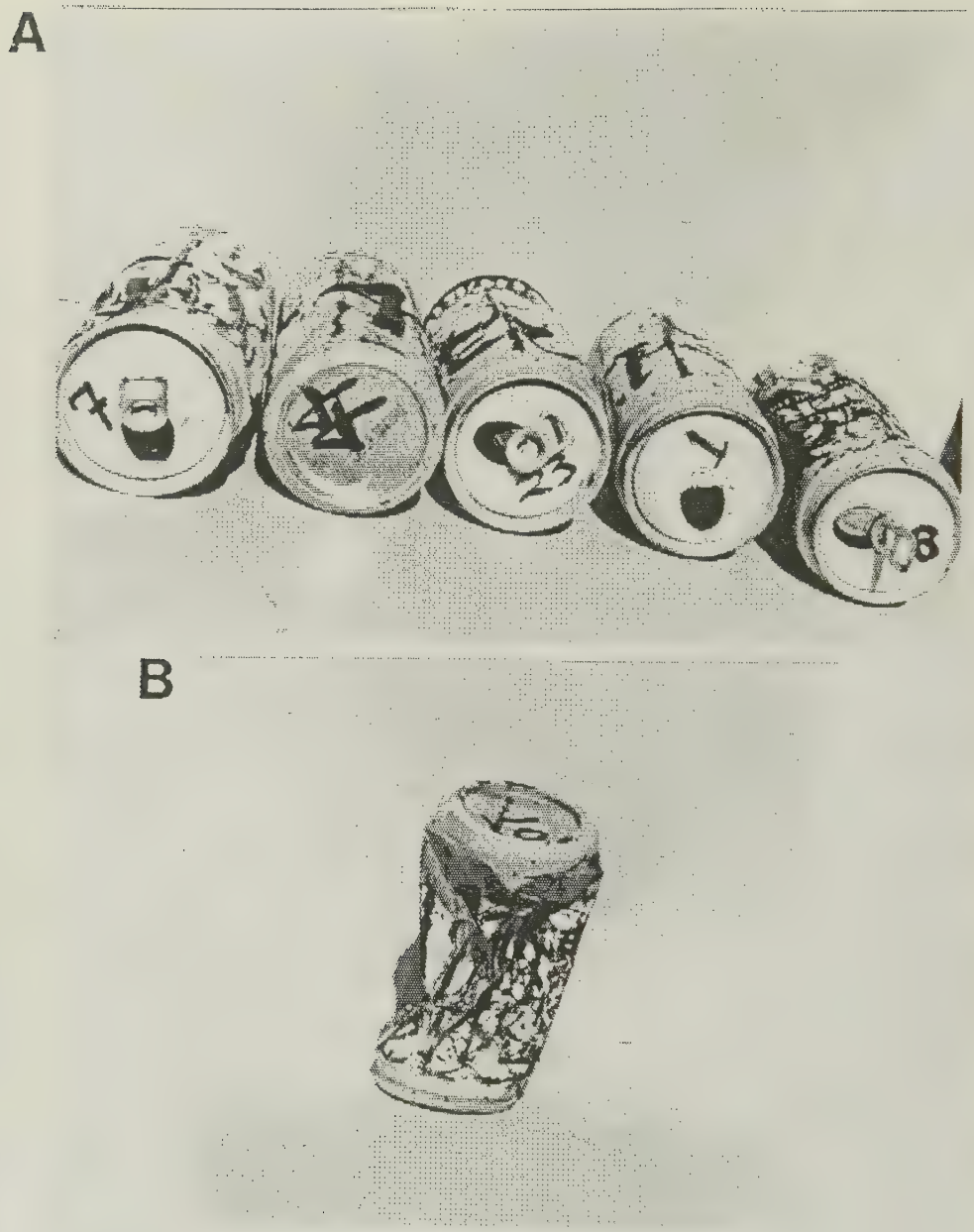


Figure 3 Damage to air cans showing polygonal deformation.
A: Can #8 on right damaged by Panamanian unit at 0.7m (shot 19).
B: Can #10 damaged by class-C cluster at 0.6m (shot 16).

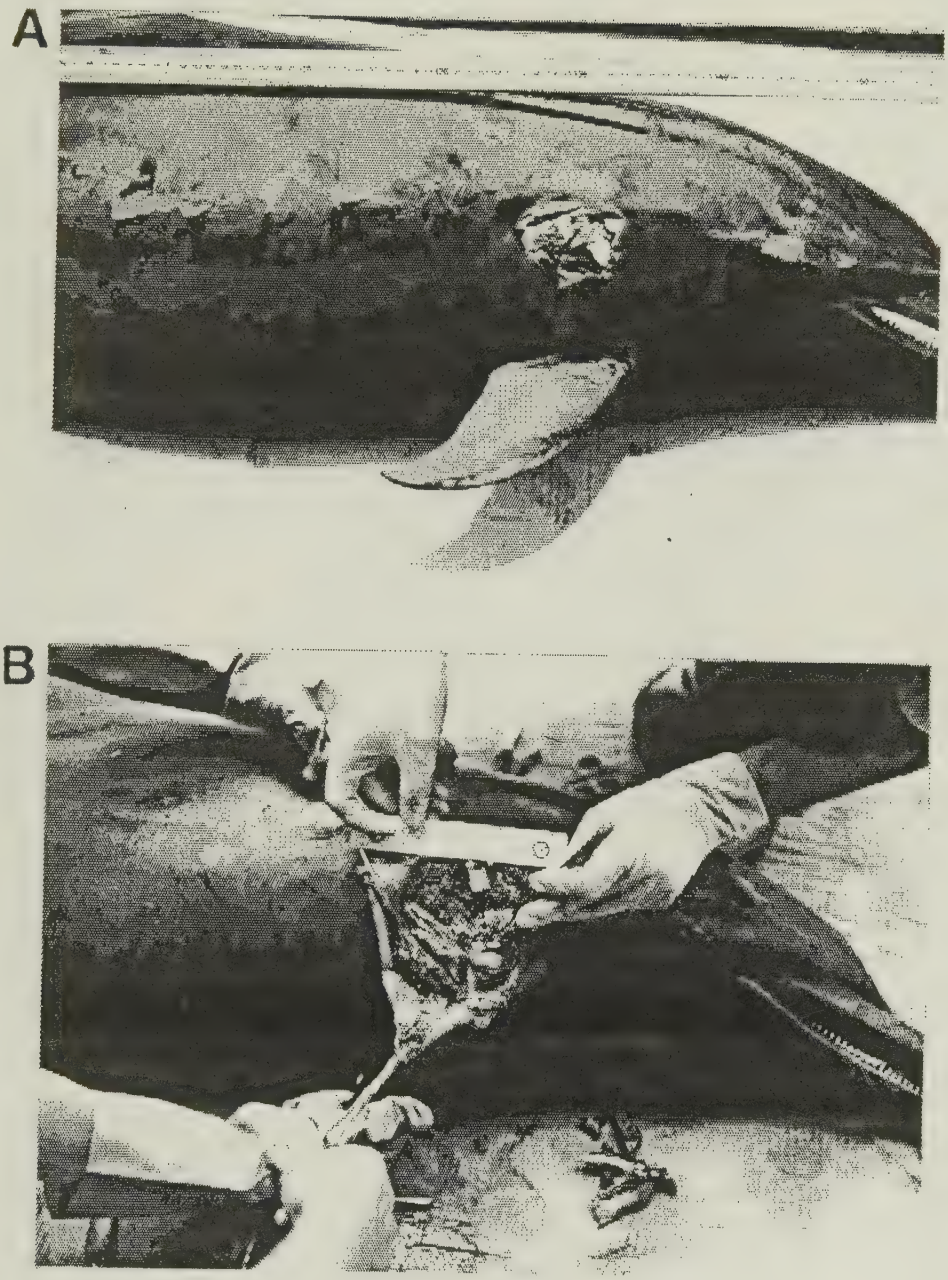


Figure 4 **A:** Damage to dolphin carcass from Panamanian unit at 0.6m. **B:** Examination of shoulder damage. Note fragments of shattered scapula in right foreground.

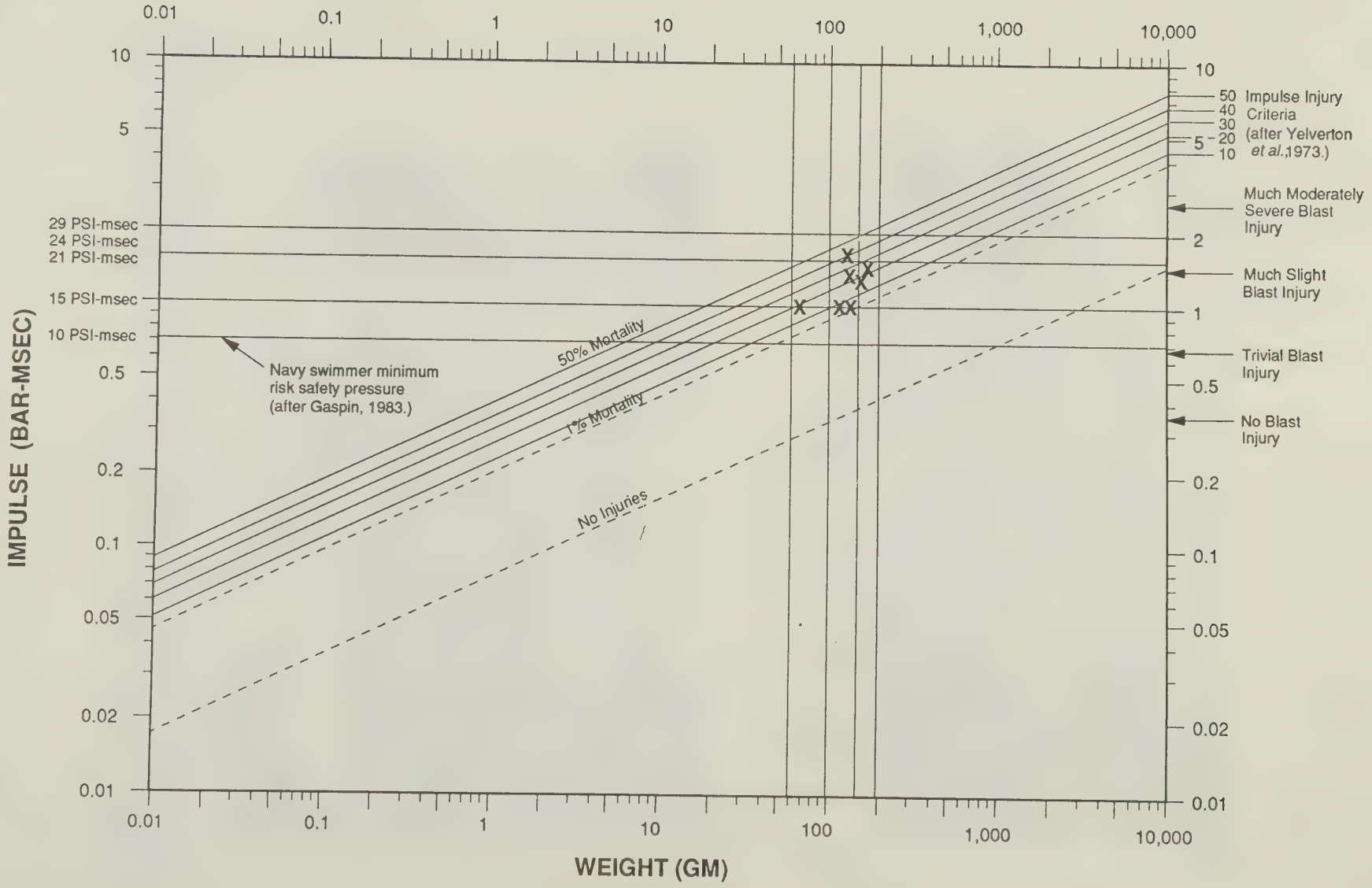


Figure 5 Plots of Weights of Fish (g) against Percent Injury and Mortality to get Impulse Pressures for seal-bomb explosions in open-water tests on 10 October 1989 (after Yelverton *et al.* 1975).

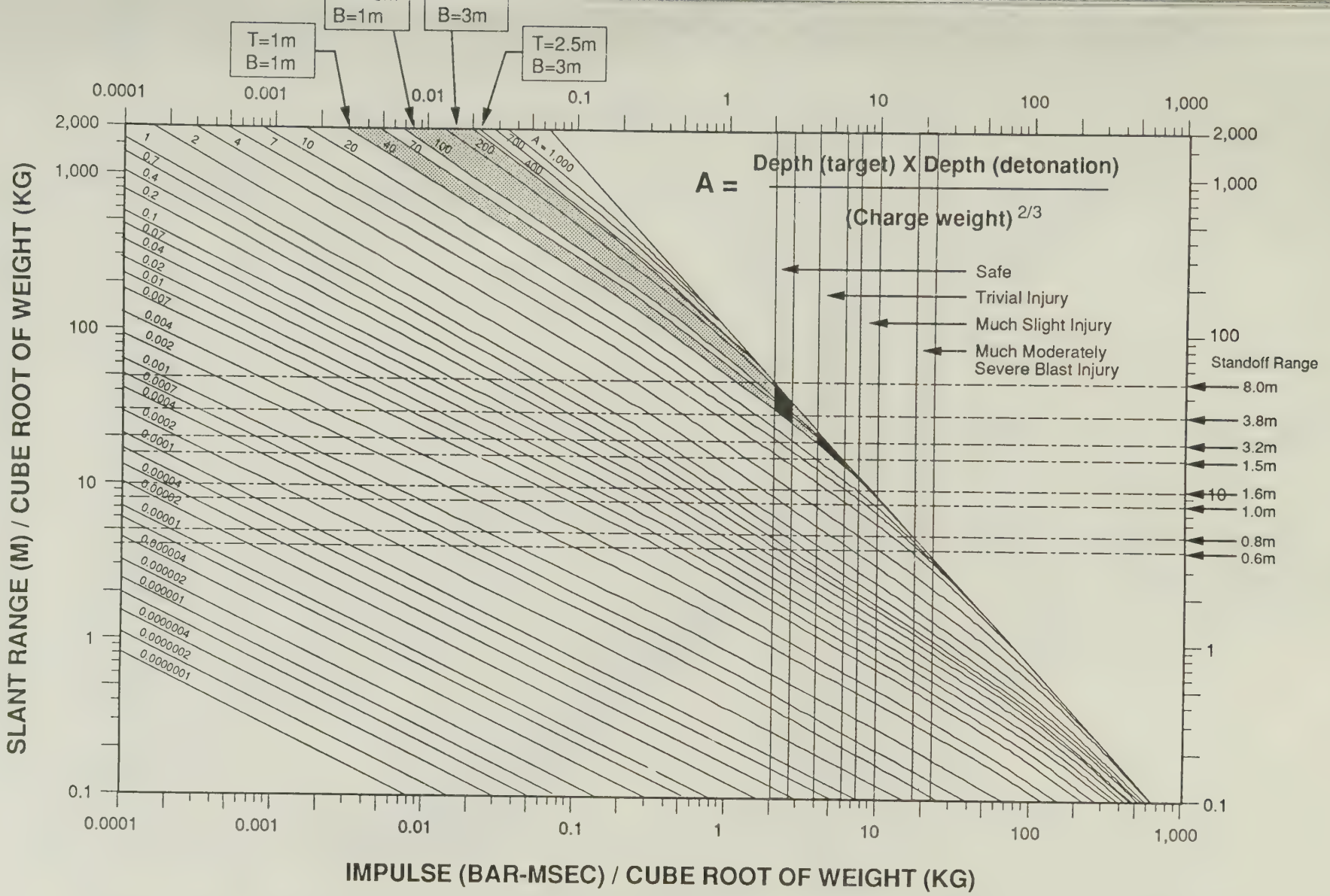


Figure 6 Use of curves from Yelverton *et al.* (1975) to predict Standoff Ranges for mammals from underwater seal-bomb explosions for 2.0, 2.5, 3.0, and 4.0g charge weights, where target (T) and bomb (B) depths are 1-1, 2.5-1, 1-3, and 2.5-3m respectively (refer to boxes in upper left). Vertical bars indicate degree of injury at distances marked by arrows on right-hand margin.

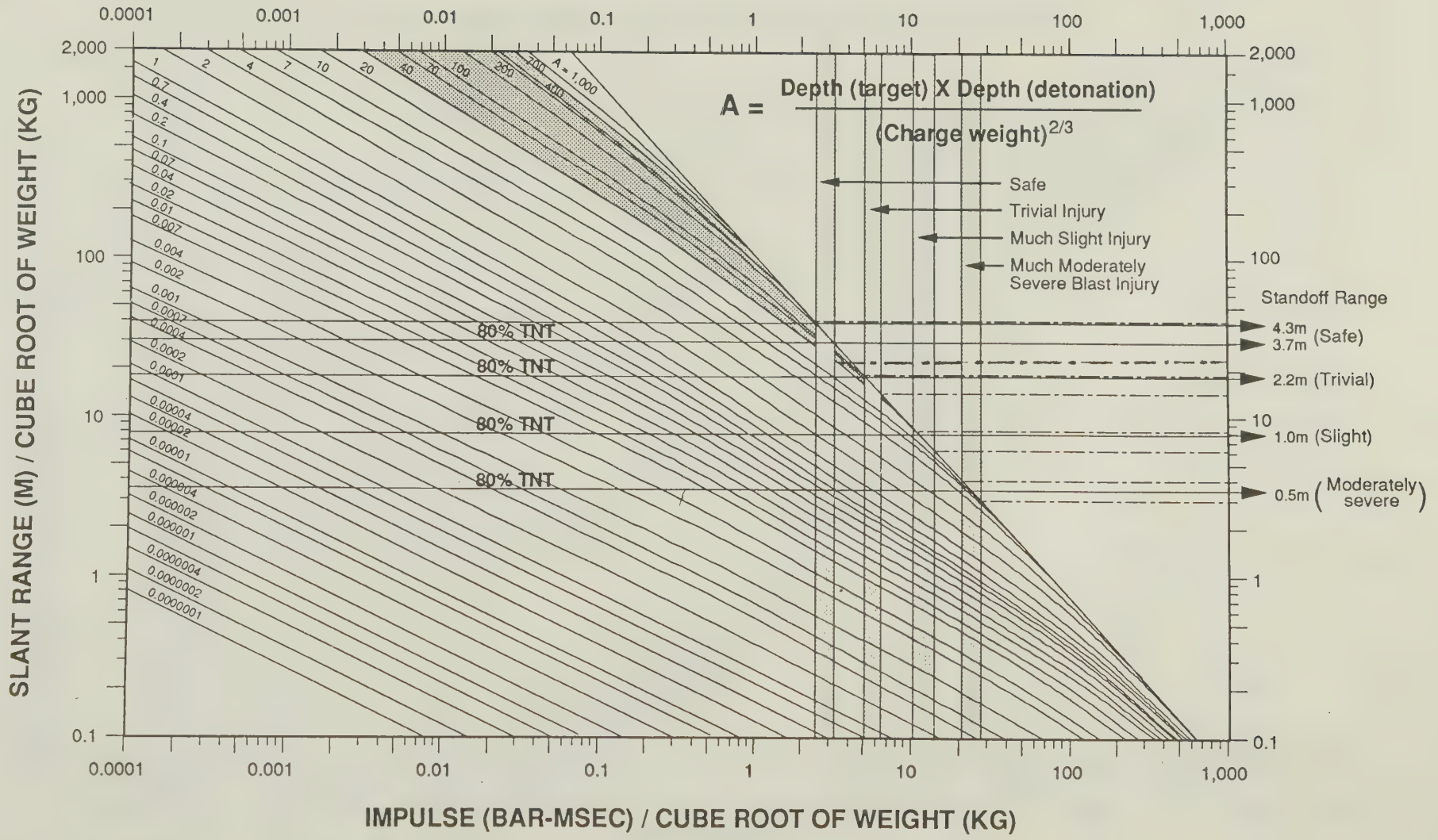


Figure 7 Use of curves from Yelverton *et al.* (1975) to predict Standoff Ranges for mammals from underwater seal-bomb explosions for standard U.S.-made unit with 2.33g of explosive, where target (T) and bomb (B) depths are 1-1, 2.5-1, 1-3, and 2.5-3m respectively, calculated for charges with 100, 80, 70, and 50% TNT equivalency. Vertical bars indicate degree of injury at distances (arrows)